Routing Management in Physical Internet Crossdocking Hubs: Study of Grouping Strategies for Truck Loading

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Abstract. The aim of the innovative Physical Internet (PI) paradigm-shifting initiative is to reverse the unsustainability situation existing in current logistic systems. In the Physical Internet, the efficient management of crossdocking hubs is a key enabler of quick and synchronized transfer of containers across interconnected logistics networks. The paper focuses on the distributed control of truck loading protocols in a rail-road crossdocking hub. It proposes grouping strategies for truck loading based on the exploitation of active containers. The grouping approach, the simulation platform and the obtained results are successively detailed.

Keywords: Crossdocking hubs, Routing, Physical Internet, Interconnected Logistics, Supply chain

1 Introduction

Montreuil [1] points out that current logistic systems are unsustainable economically, environmentally and socially. The aim of the innovative Physical Internet (PI or π) paradigm-shifting initiative is to reverse this situation from three points of view:

- The economic goal is reducing by an order of magnitude the global costs induced by logistics and unlocking significant business opportunities;
- The environmental goal is reducing by an order of magnitude the logistics induced global energy consumption, greenhouse gas emission and pollution;
- The societal goal is enhancing the quality of life of the different actors (e.g. truckers, logistic workers…) implied in the logistic systems, and of society at large through better goods accessibility and mobility.

The PI concept is based on a metaphor of the Digital Internet. By analogy with data packets, the goods are encapsulated in modular, reusable and smart containers, called π-containers. The π-containers range in modular dimensions from large to small. The ubiquitous usage of π-containers will make it possible for any company to handle and store any company's products because they will not be handling and storing products per se. The efficient management of PI crossdocking hubs is a key enabler of quick and synchronized transfer of π-containers through interconnected logistics networks. It has been shown in a previous study [2] that truck loading activities in PI crossdocking hubs are crucial activities that should be studied in depth. The aim of this paper is to focus on this issue and to propose an approach and strategies for pre-loading grouping of π-containers to reduce the overall loading time.

The paper is structured as follows. The management issues of PI crossdocking hubs are introduced section 2. Section 3 focuses on the grouping approach and introduces alternative strategies. The simulation platform, protocol and results are then detailed in section 4. Finally a conclusion and some prospects are offered in section 5.

2 Physical Internet context

The specificities of the Physical Internet crossdocking hubs (denoted π-hubs hereafter) are introduced in the following sections.

2.1 From the classical crossdock to π-hub

In a usual crossdocking approach, supply and demand chains are coupled and synchronized, replacing or greatly minimizing inventory buffers [3]. However usual crossdocking hubs are not designed for supporting the Physical Internet. Several points differentiate a π-hub from a usual crossdocking hub. The main difference is based on the foundation principles of the PI: usual crossdocking hubs are restricted to some suppliers and/or clients of a company, while the PI proposes an open meshed approach. The π-hubs are conceived by default to be open to any π-certified users and to handle multiple dynamically selected sources and destinations.

From a technical point of view, several other differences can also be noticed:

- First, existing crossdocking hubs handle all kinds of freight (e.g. cartons, shrink-wrapped pallets) while π-hubs are specifically designed to deal with modular and standard π-containers.
- In usual hubs, depending of the type of freight, the transportation is executed manually (e.g. by workers using forklifts for palletized freight) or based on dedicated automated systems [4]. As a π-hub handles only smart, standardized modular π-containers, it opens the way for high automation and high reactiveness. An automated π-hub can be mainly composed of a flexible network of π-conveyors, allowing decomposition, sorting and re-composition of the π-containers. The π-conveyors allow moving π-containers in the four directions (front, back, left and right) as depicted in Figure 1.
- In a π-hub, a π-container must not be considered as only a standardized container with a cargo as in usual crossdocks. It has informational, communicational and decisional capacities and can play an "active" role in the crossdocking process.

2.2 Illustration of a road-rail π-hub

Different π-hub combinations may exist: road-road, road-rail, etc. In order to make clear the nature of π-hubs, Figure 1 presents an illustrative example of a rail→road π-hub, inspired from the works of [5]. This rail→road π-hub aims to realize smooth interconnections between trains and trucks in shortest time. It allows the unloading of five wagons simultaneously and is composed of a sorting area and a manoeuvring area.

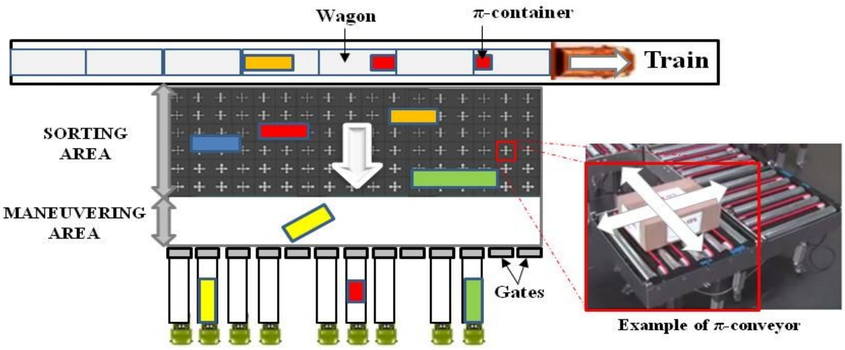

Fig. 1. Example of a rail→road π-hub (inspired from [5])

The sorting area is used to sort the inbound π-containers and to route them toward the manoeuvring area. The sorting area is composed of a grid of π-conveyors as depicted in Figure 1. The manoeuvring area allows returning the π-containers and moving them towards the different gates, where trucks are located. Note that this rail→road π-hub can be extended into a bilateral rail-road π-hub by adding to the right a road→rail π-hub section.

2.3 Current issues in π-hub management

In the recent PI research field, the management of π-hubs constitutes an important issue [5]. The quick and flexible transfer of π-containers from one transporter to another is the core activity of a π-hub. Different modal transfers (e.g., road to rail, road to road, ship to rail) are currently distinguished in PI networks and several problems must then be considered in the crossdocking process:

- Transporter scheduling in short term horizon: the π-hub gates are considered as resources (used by the trucks by example) that have to be scheduled. This problem requires deciding on the succession of inbound and outbound transporters (trucks, ships, etc.) at the gates of a π-hub.
- Allocation of π-containers to transporters: this problem consists in choosing the most appropriate loading of trucks with the π-containers unloaded from inbound train or trucks.
- Routing of π-containers across the π-hub: Once the π-containers have been unloaded from their inbound transporter, they are engaged in a preparation process that will get them composed appropriately with other π-containers and brought in time to be loaded in their outbound transporter.

The management of a π-hub as studied in this paper must concurrently deal with two types of perturbations:

- The external perturbations, taking into account the following degrees of variability and uncertainty:
  - The flow of π-containers to be treated can vary through time, both in terms of quantity, size mix and destination mix.
  - The incoming flow will normally be known to arrive a few hours ahead of time. Considering a train coming from a preceding π-hub, the information relative to its load is forwarded upon its departure. However in a rail→road hub, if a train is delayed, another train may enter the π-hub while the trucks are already positioned for the delayed train. Thus the control system should reactively solve a problem that was unknown until that moment.
- The internal perturbations concern mainly the network of π-conveyors: A part of the flexible conveying network can be out of order due to breakdowns or curative maintenance operations.

The next part presents a literature review in the field of π-hub control.

2.4 Short survey of π-hub control

In the recent PI field, a few studies have been already done on π-hub control. In [5] and [6], the authors propose respectively a specific design of a rail→road π-hub and of a road-based π-hub. The primary goal of these studies was to produce a functional design that performed at an acceptable level in terms of user key performance indicators and to explore its robustness with various flows. A simulation study has allowed to model and to validate the normal functioning of a π-hub. However, no perturbation on the conveying system or on the loading/unloading processes has been taken into account.

Moreover, at this point of development of the PI, very few research works have also addressed the routing problems in a π-hub [5, 7]. Recent works [8, 9] have proposed decentralized control to prevent deadlocks on a grid of π-conveyors. However these previous works deal with only small-size goods located on a unique conveying module and do not take into account different sizes of containers.

In [2], the authors study the routing of π-containers in a road-rail π-hub inspired from [5, 10]. They aimed to find the parameters that have a significant impact on the π-hub effectiveness. The parameters studied were the π-containers' size, their number of movements in the system, the numbers of conflicts between π-containers and the loading time of π-containers in trucks. The works presented in the next section are in the continuity of [2] and focus more precisely on the grouping of π-containers. Only the routing problem is treated in this paper. Interested readers can refer to [11] for a study of the allocation problem and a proposition of a formal model for the π-hub.

3 Grouping approach and strategies

Simulations presented in [2] have shown that the loading of trucks is the bottleneck activity of the π-hub. Thus to optimize the transfer of π-containers, an interesting solution is to assemble several small π-containers in front of the truck prior to loading and to load them as a single composed π-container. This section proposes a grouping approach using active π-containers.

Several approaches can be adopted (i.e. distributed or centralised) to solve the truck loading problem in a rail→road π-hub. In this paper, the concept of active product [12] is chosen for reactivity and adaptability reasons to face uncertainties and perturbations. Usually, distributed approaches can suffer from myopic behaviors [13]. In this case study, myopic behaviors cannot occur because each π-container already knows its destination truck. Moreover, for each truck a sole initiator can exist at a given time. In the retained approach, communicational and decisional capabilities are embedded in π-containers. These play an active role by creating groups of π-containers before being loaded onto a truck to reduce the loading queue.

The grouping approach, aiming at loading several π-containers while respecting a determined grouping size, is detailed below and depicted in figure 2 for a three-container group (initiator and two other containers).

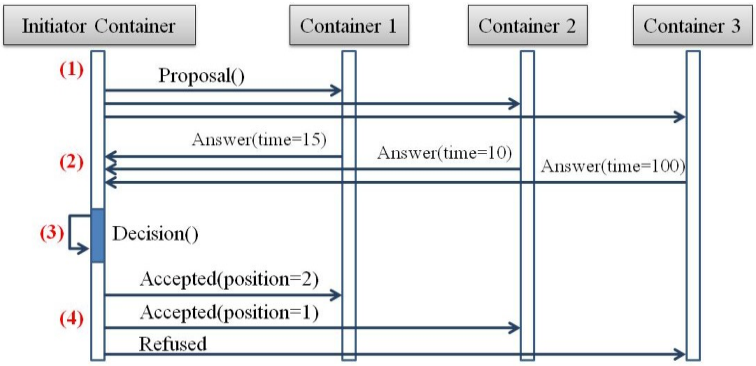

Fig. 2. Example of container grouping approach

(1) Proposal: The first π-container (the initiator) that arrives in front of its destination truck sends a "grouping proposal" to know the π-containers that could be grouped and loaded with it.
(2) Answer: The concerned π-containers answer to it by giving their arrival time.
(3) Decision: The initiator chooses the π-containers based on two parameters:
- the grouping size limit (defined by the strategy chosen), that provides the maximum number of π-containers in the group,
- the arrival times sent by the other π-containers. The initiator container chooses the π-containers with the earliest arrival times to form the group until the size limit.

(4) Choice diffusion: The initiator container sends to the chosen π-containers their specific location in the group formed at its right. It also sends a refusal to the unselected π-containers.

Using this approach, three strategies can be used to determine the grouping size limit (used in step 3 of Figure 2). First, all the containers going to the same truck are grouped and loaded at once (i.e. infinite limit). Second, the number of containers in each group is limited statically to avoid disturbing the loading of the neighbor trucks. And third, the number of containers in each group is limited dynamically by extending them if the gates on the right are not used (no truck allocated to the neighbor gates). Figure 3 presents a view of the simulator during this grouping approach and the location of containers within the π-hub.

To validate our approach, the next section presents the simulation environment, protocol and the results for each one of these strategies.

4 Simulation protocol and results

The grouping approach is evaluated through a simulation experiment by using the Netlogo multi-agent environment. This environment is well adapted for rapid prototyping of reactive multi-agent systems and provides user-friendly interfaces. The behaviors of the active π-containers are represented by agents with processing, communicational and decisional capabilities. Figure 3 presents a screenshot of the simulator during the grouping process presented in Figure 2.

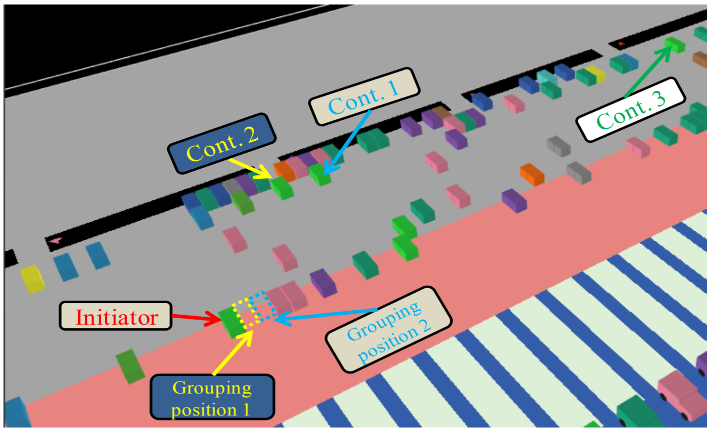

Fig. 3. View of the simulator describing a three-container grouping

Four series of simulations were performed: the first one presents a basic truck loading without grouping and the three others respectively concern the three grouping strategies presented above. Each simulation experiment contains 2000 runs of the simulator with a random positioning of trucks and π-containers. The train is assumed loaded with only small unitary π-containers that constitute the more interesting case study as highlighted in [2]. The different simulation experiments are as follows:

Sim. #1: π-containers route themselves into the π-hub and are loaded without grouping (i.e. grouping size limit = 1).
Sim. #2: the first π-container that reaches a truck waits for all the containers that go to the same truck to be loaded at once (i.e. grouping size limit = remaining space in the truck).
Sim. #3: the groups of π-containers are limited to three containers to avoid disturbing neighbor loading gates (i.e. grouping size limit = space between two gates = 3).
Sim. #4: the grouping size limit is now dynamic and can be extended if the neighbor loading gate is not used (i.e. 3 ≤ grouping size limit ≤ remaining space in the truck).

The performance indicator is the evacuation time that represents the time between unloading the first π-container from the train and loading the last π-container onto its truck. Table 1 summarizes the different simulation results.

Table 1. Simulations results

Evacuation Time for 2000 runs (sec)	Simulations #1	#2	#3	#4
Average	963	634	628	623
Standard Deviation	122	46	42	43
Min	664	524	520	504
Max	1744	816	800	828

First these simulations show that the grouping of containers is efficient. The evacuation time for simulation experiment #2 is around 30% lower than the one for the first baseline scenario (without grouping). The grouping of containers greatly reduces the evacuation time with several containers going in the same truck. Thus the maximum value is divided by two, which implies a lower standard deviation for the simulation experiment.

However, the simulations in experiment #2 exhibit some blocking situations where some truck loading is delayed because the place in front of the truck is occupied by the π-container grouping of the truck on the left. In simulation experiment #3, these blocking situations were avoided because the group size limit was set to 3. The extension of the grouping size limit in simulation experiment #4 does not impact most of the simulations. But in some cases, the evacuation time was lowered by 120 seconds (i.e. one loading time). Indeed, with this modification six containers can be loaded at once (if the gate on the right is not used) instead of two times three containers.

If the scenario includes a lot of π-containers going to the same truck, the strategies tested in experiments #3 or #4 have to be chosen. If there are some gates that are not used in the scenario, the strategy simulated in experiment #4 should be used to provide better results. So the strategies proposed consider an increasing number of specific cases without impacting the overall results. Indeed, the enhanced strategies respectively lower the evacuation time of simulation experiment #2 by 1% to 2% in average over 2000 runs, while taking into account the specific scenarios.

5 Conclusion

This paper presented a study of routing inside a π-hub and focused more particularly on the loading of π-containers onto trucks. The aim of this paper was to show the impact of different grouping strategies using the concept of π-container activeness.

The simulations proposed showed that the grouping of containers has significant value. It lowers the evacuation time of the system by 30%. The grouping of containers could be made using different parameters like the number of containers grouped or the time waited by containers before loading. This paper illustrated this with some grouping strategies dedicated to specific scenarios.

Next studies should first consider other performance indicators like the departure time of each truck or π-container. It could make easier the evaluation of specific scenarios and of the corresponding strategies. Another perspective is to include internal perturbations to prove the robustness of the routing mechanism in a disrupted environment. Finally, the routing approach could be extended for example by taking into account future states of the system in the decisional and grouping mechanism.

6 References

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